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# Progress in Dark Matter Research

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# Chapter 1

## Quest for Fats: Roles for a Fat Dark Matter (WIMPZILLA)

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Since 1990's the detection of extremely energetic air showers and precise astronomical measurements have proved that our knowledge about fundamental laws of Nature is far from being complete. These observations have found convincing evidences against two popular believes: The spectrum of Cosmic Rays would have a steep cutoff at energies around  $10^{19}eV$  (GZK cutoff) and the contravortial quantity called Cosmological Constant (dark energy) should be strictly zero. They have been important additions to the yet unsolved mystery of the nature of dark matter.

For both phenomena many models have been suggested. The top-down model - decay of a Superheavy Dark Matter (SDM), also called WIMPZILLA as the origin of the Ultra High Energy Cosmic Rays (UHECRs) - is one of the most favorite candidates. Here we show that a meaningful constraints on the mass, lifetime and cosmological contribution of SDM is possible only if the energy dissipation of the remnants is precisely taken into account. We discuss the simulation of relevant processes and their evolution in the cosmological environment. We show that such a dark matter can be the dominant component of Cold Dark Matter (CDM) with a relatively short lifetime. Moreover, the equation of State of the Universe in this model fits the Supernova type Ia data better than a stable dark matter. If a small fraction of the mass of the SDM decays to an axion-like scalar field, its condensation can also explain the dark energy without need for extreme fine tuning of the parameters. Presumably, a meta-stable dark matter can explain 3 mysteries of Physics and Cosmology. Finally we review some of the particle physics and cosmological issues related to SDM and its associated quintessence field.

## 1.1 Introduction

First evidences for the existence of a dark component of matter with only gravitational effects in cosmological environment (galaxy clusters) was discovered in 1930's [1] and investigated more in detail with first measurement of galaxy-galaxy correlation during 1950's [2]. It was however only after 1980's large galaxy surveys and measurement of Milky Way velocity curve [4] that its existence became an established fact. Roughly at the same time in Particle Physics, growing interest and efforts were dedicated to Super Symmetric (SUSY) models [5]. Naturally many cosmologist and particle physicists found supersymmetric partners of ordinary matter and more specially the lightest of them (LSP) as the best candidate for the mysterious Dark Matter (DM).

Generally, CDM is assumed to be composed of Weakly Interacting Massive Particles (WIMPs). Until today neither of efforts for direct detection of these particles nor searches for their signature in astronomical data have found any reliable signal. Search for SUSY particles including LSP in accelerators is also in the same situation. Nonetheless, next generation of high energy particle colliders like LHC have a good chance to detect supersymmetric particles if they exist and if their mass is less than few hundred GeV [6].

Constraints on the coupling of WIMPs to baryonic matter depend on the assumptions about their mass and their flux around the Solar system, the type of their interaction with baryonic matter (branching ratio, spin dependence, etc.) and their self-annihilation cross-section. These quantities are usually estimated based on the assumption that dark matter (WIMPs) are LSP. The reason for this apriori is that in the light of new experiments other potential candidates like left hand neutrinos and QCD axion are proved to have very small contribution to the total CDM [7] [8].

Minimal Super Symmetry Model (MSSM) has more than 100 parameters and therefore should be considered not as a real model but as a framework. Even its constrained form (CMSSM) [9], depends on multiple parameters like Higgs multiplet mass parameter  $\mu$ , Higgs masses and ratio of Vacuum Expectation Values (VEVs)  $\tan \beta$ , gaugino mass  $m_{1/2}$  and scalars' mass  $m_0$  at unification scale, etc. Many but probably not all of these parameters can be determined by LHC if SUSY scale is not much higher than electroweak scale presumably  $\sim 1TeV$  [10]. Part of the parameter space is already excluded by recent precise measurement of WMAP [7], limits on the mass of Higgs, muon anomalous magnetic momentum  $g_\mu - 2$  and neutrino mixing and texture [11] [6]. Nonetheless, large part of the parameter space is yet possible. In addition, relaxing some of the constraints considered as being *realistic* increases the allowed ranges. Consequently the contribution of LSP in DM is not well determined and a large number of combinations are apriori permitted. For instance, the region with neutralino mass  $m_\chi \gtrsim 1.4TeV$  gives a contribution which contradicts WMAP observation and therefore is ruled out. By contrast many other combinations of

parameters can lead to a contribution much smaller than observed  $\Omega_{CDM}$ .

LSP is usually considered to be a neutralino, i.e. the lightest gauginos which is assumed to be a mixture of bino and higgsino. Its mass can also be very close to stau mass. LSP must be stable or has a long lifetime if  $\mathcal{R}$ -parity is conserved, otherwise most probably (but it depends again on the other parameters) it will have a short lifetime and can not contribute to the dark matter. Therefore even the detection of LSP in accelerators is not a proof that dark matter is LSP. One has to find its lifetime which is not very easy if it does not decay inside detectors. The only possibility in a near future to find such a signal is astronomical data. At present no evidence has been found, but as usual channels to search for such a signal as well as self-interaction of LSP depend on the unknown parameters of SUSY models.

Cosmological contribution of a stable or meta-stable particle - a decaying particle with a lifetime of order or longer than present age of the Universe - depends on its mass, the cross-section of its interaction with itself (self annihilation) and other species, its kinematic i.e. if it had sufficient interactions in the early Universe - presumably after inflation and reheating - such that its distribution becomes thermal. To make a rough estimation about the relation between mass and interaction cross-sections we can use a simple form of Boltzmann equation for cosmological evolution of  $n(t)$  the number density of a stable species  $X$  (thermal or chemical equilibrium is not assumed):

$$\frac{dn}{dt} = -3(w_q + 1)Hn - \langle\sigma v\rangle n^2 - \langle\sigma_N v\rangle nN + \langle\sigma_n v\rangle N^2 \quad (1.1)$$

where  $w_q$  determines the equation of state of  $X$ ,  $\sigma$ ,  $\sigma_N$  and  $\sigma_n$  are respectively total cross-section for its self-annihilation, its interaction with other particles and its production in the interaction of other particles collectively called  $N$ ,  $v$  is a nominal velocity determined by kinetic energy of particles, and  $H(t) = \dot{a}/a$  is the Hubble Constant at time  $t$ . For weak interacting particle (as a DM should be) one expects that the second and third terms on the right hand side of (1.1) must be less significant than others. Neglecting these terms, the decoupling of the particle happens when expansion term becomes dominant. If at this time the value of Hubble Constant is determined by other species, the only factor which determines today contribution of  $X$  in DM is its self-annihilating cross-section and its mass. Higher masses need a larger cross-section (or lower initial density) to respect the observed mass constraint. Conversely, if  $X$  is relatively light and its self-annihilation cross-section is relatively high, its contribution to CDM can be small. If the claimed deviation of  $g_\mu - 2$  from predicted value by Standard Model is confirmed, this quantity put a more stringent lower limit on the self-annihilation cross-section than Higgs lower mass limit [11]. As this limit is much higher than the limit from  $\Omega_{CDM}$ , either LSP has only a small contribution in the CDM (roughly comparable to the contribution of baryonic matter) or its mass must be  $m_\chi \gtrsim 200\text{GeV}$ , just in the limit of LHC observation possibility.

In summary it is worth to look for other potential components for CDM although it is not yet sure that in addition to LSP we need another stable or meta stable component. Above arguments are not in fact the only motivations for looking for other alternatives. Here we briefly review other reasons in favor of non-LSP candidates for dark matter and specially ones with masses around Grand Unification (GUT) scale.

In the theoretical side various phenomena at SUSY scale and beyond are able to make new hierarchy of masses and conserved quantum numbers. Many models can found in literature. Some examples are listed in [12]<sup>1</sup>. For instance in gauge mediated SUSY breaking models one of the reasons for supersymmetry breaking in the hidden sector can be the condensation of gauginos which can also lead to gauge symmetry breaking (For a review of SUSY breaking mechanisms see [13]). If this creates a split in the masses in the hidden sector similar to  $SU(2) - SU(3)$  splitting in SM sector, some of fields can get strong interactions. This phenomenon along with existence of conserved (or approximately conserved) global symmetries due to splitting can make very massive and long lifetime particles. Discrete symmetries can also make massive fields like messenger bosons meta-stable and therefore a good candidate for SDM [14].

Since 1998 various observations including the observation of high redshift Supernovae Type Ia [15] [16], precise CMB anisotropy observation by WMAP [7], large galaxy surveys like SDSS [17] and correlation between them [18] as well as comparison between images of lensed distance objects [19] show that the energy contents of the Universe is dominated by a mysterious form of energy called Dark Energy (DE) with an equation of state very close to a cosmological constant. In the following sections we will argue in detail that somehow there must be a relation between dark matter and dark energy. Some of the candidate theories which can provide solutions for mass hierarchy contain also axion like particles [20] which can play the role of a Quintessence field [21].

On the experimental side the main motivation for considering scenarios in which part of the dark matter is a very heavy particle is the mystery of observed Ultra High Energy Cosmic Rays (UHECRs). Study of such possibility is the main subject of this chapter. We therefore leave the detail explanation to the next section and conclude this introduction by summarizing the contents of following sections.

In this chapter we show that apriori it is possible to relate three problems we mentioned in above i.e. dark matter, dark energy and UHECRs. Our solution assumes the existence of a super heavy dark matter. We first obtain constraints on the properties of these particles like mass and lifetime. Then we study their effect on the cosmological equation of state. We also consider the role they can have in producing a light scalar field which is able to explain the dark energy and its

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<sup>1</sup>In particle physics for each of these issues large number of models have been investigated. As it is impossible to list all these works here, we give only a few examples of ideas and therefore references mentioned here as well as variety of ideas are not exclusive.



equation of state. Finally we briefly discuss some of particles physics models with proper field contents and the issue of their production in the real Universe.

## 1.2 Ultra High Energy Cosmic Rays

Principal motivation for existence of an ultra heavy meta-stable particle has not been originally the quest for dark matter but the observation of Ultra High Energy Cosmic Rays (UHECRs) by large air shower detectors [22] [23] [24] [25] (For a review of UHECRs detection and observed properties see [84]). The predicted GZK cutoff [27] in the spectrum of CRs at energies around  $\gtrsim 10^{19}eV$  due to interaction with CMB and IR photons restricts the distance to the source to less than  $\sim 20 - 50Mpc$ , depending on the injection rate, spectrum, and on the amount of background radiations specially radio and IR. Optical depth of protons around GZK cutoff can be roughly estimated by  $\tau_{opt} \approx \sigma n_{cmb}$ . For  $\sigma \approx 0.45mb$  [28] close to  $\pi$  production resonance, the probability of propagation without interaction in a distance of  $30Mpc$  is at most  $\sim 10^{-8}$ .

Order of magnitude statistics of observed events is:  $\sim 1000$  events with  $E \gtrsim 10^{19}eV$ ,  $\sim 100$  with  $E \gtrsim 4 \times 10^{19}eV$  and 20 events with  $E > 10^{20}eV$  [29] [30] including one with  $E \sim 10^{21}eV$  [23]. The UHECRs spectrum roughly has the same power-law shape up to around  $E \sim 10^{19}eV$ . But at higher energies spectrum becomes flatter in contrast to prediction of GZK cutoff.

Composition of the primary particles [32] [33] can be estimated from the shower, specially from maximum position and elongation rate of muons in the atmosphere. Uncertainties in determination of primaries composition include dependence on the hadrons interaction/fragmentation model at high energies [34] and on the detector response. However, most analyses are in favor of a hadronic particles  $p, \bar{p}, n, \bar{n}$ . Light nuclei like  $D$  or  $He$  can not be completely ruled out [23] [32] [33]. This composition is very different from one at lower energies which is dominated by  $Fe$  nuclei and is probably an evidence of a different origin for Cosmic Rays with  $E \gtrsim 10^{19}eV$ . Some authors have tried to explain this modification of composition by disintegration of Iron and other heavy nuclei in the cosmic photon field. By considering a unique injection energy of  $10^{22}eV$  for  $Fe$  (i.e.  $\sim 10^{20}eV$  per nucleon) [35] a roughly constant distribution of nucleons up to a distance of  $50Mpc$  from the source has been found. It has been claimed that up to simulation precision this result does not strongly depend on the extra-galactic magnetic field [35]. By contrast, the latter affects the flux of Iron and other nuclei. We will see later that high energy nucleons lose large amount of energy to CMB and IR background during propagation and a constant distribution does not seem realistic. In fact another similar study [36] finds that when the injection energy is limited to  $Z \times 2 \times 10^{19}eV$ , at the same distance of  $\sim 50Mpc$ , protons are concentrated in  $E \lesssim 10^{19}eV$  and therefore it seems that it is difficult to explain the composition change by disintegration. Correlation between Super Galactic Plane and clustering in 2 doublets and one triplet was

claimed [29] [38] [30], but denied by other analyses [39] [31]. Moreover, apparent clustering of events can originate from caustics generated by the galactic magnetic field [40] [41]

### 1.2.1 Origin of UHECRs

Few phenomena in the history of physics have had as many suggested origins as UHECRs. From the most classical sources (if the word *classic* makes any sense when we talk about the most extreme objects and environments we can find today in the Universe) i.e. shocks in the supernovae remnants or somehow more exotic astronomical objects like accretion disk around supermassive black holes in Active Galactic Nuclei (AGNs) or dormant AGNs like one in the center of our own galaxy, up to modifications in some of the most fundamental laws of physics like Lorentz invariance of the space-time have been proposed as the origin of UHECRs.

Here we discuss some of conventional and exotic potential sources of UHECRs very briefly. Our main purpose is to show that a SDM i.e. top-down solution is at present one of the most plausible candidate until Auger Observatory solves issues like composition of primaries, anisotropy and its relation with galactic halo and local matter over-densities (like Virgo Cluster), ultimate break in the high energy tail of the spectrum, etc.

#### Conventional Candidates

Conventional accelerators can hardly accelerate protons to energies requested for UHECRs. Maximum energy a charged particle can be accelerated to by Fermi mechanism [42] is<sup>2</sup>:

$$E_{max} = \left( \frac{3\eta BR^2}{2eZ} \right)^{\frac{1}{4}} m \quad (1.2)$$

where  $B$  is the magnetic field,  $R$  is the size of acceleration zone ( $R \lesssim r_{Larmor} = E/eB$ ), and  $\eta B$  is the effective electric field in the direction of particles trajectory. In this formula the only source of energy loss is considered to be synchrotron radiation. Using (1.2) and approximate knowledge about size and magnetic field of astronomical objects Table 1.1 shows maximum energy obtainable by Fermi acceleration in some of astronomical objects proposed as the source of UHECRs. Particles energy after escaping from acceleration zone is certainly smaller than what is shown in this table partly because of adiabatic deceleration when the magnetic field becomes small and partly because of high probability of interaction with particles in the acceleration zone or its outskirts [43]. The suggested solution is the change of particle type from proton to neutron which then can escape the adiabatic deceleration [44]. But this needs interaction with other particles i.e. loss of significant

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<sup>2</sup>Through this chapter we use unit system in which  $c = \hbar = 1$

Table 1.1: Maximum acceleration energy for protons by Fermi Mechanism

Object	Size	$B(G)$	$E_{max}()$	
Supernova Remnant [45]	$1pc$	$\sim 10^{-5} - 10^{-5}$	$\sim 10^6 - 10^7$	Too small.
Close to central black hole in AGNs [46] / Quasar Remnants and Dormant AGNs [47]	$R \sim 0.1pc$	$\sim 30$	$\sim 10^{12} - 10^{13}$	Too far (see also the text).
Shock front of relativistic jets	$\sim 10^{-3}pc$	$\sim 5$	$\sim 10^{10} - 10^{11}$	Too small for events $E \gtrsim 10^{20} eV$ .
Hot Spots, radio galaxies	$\sim 1 - 10pc$	$\sim 10^{-4}$	$\sim 10^{11} - 10^{12}$	Too far.
GRBs [48]	$\lesssim 0.1pc$	$\sim 10^4$	$\sim 10^{10} - 10^{11}$	Energy and unconfirmed assumptions [51].
Pulsars (Magnetars) [49]	$\sim \text{Few km}$	$\sim 10^{14} - 10^{15}$	$\sim 10^{12} - 10^{13}$	Too rare.

amount of energy [43]. Adiabatic expansion problem can also be solved by an abrupt change in the magnetic field, but this needs a fine tuning of the source structure.

Other acceleration mechanisms like Alfvén waves [50] and multi-front shocks [51] which can produce somehow higher maximum acceleration energies have been also proposed. However they don't solve the problem of energy loss completely. In addition, one of the most important constraints on acceleration models is the unobserved excess of TeV  $\gamma$ -rays [43] and high energy neutrinos (although physics of high energy neutrinos at present is too uncertain to use them as a constraint). In the case of GRBs, a simulation [52] of cosmological distribution of sources with a power-law flux of UHECRs shows that the expected flux on Earth is much lower than observed values.

### Correlation with Astronomical Objects

Many efforts have been dedicated to correlate UHECRs to astronomical objects, but practically all of them have been failed or were not confirmed by further investigations. The deflection in galactic magnetic field can be the reason if sources of UHECRs are extra-galactic objects. Our ignorance of the geometry and strength of magnetic in the galaxy and also in the local group does not permit a correct reconstruction of original direction of the primaries.

Between all the correlation attempts there is probably one with interesting results because it does not try to correlate events one-by-one, but considers the global rate of correlation between UHECRs and nearby elliptical galaxies [53]. Most of AGNs are in this type of galaxies. As the lifetime of AGNs is short - of order of

$10^7$  years - one can suppose that dormant AGNs are in the center of these galaxies and the magnetic field of a Kerr black hole in their center can accelerate particles to very high energies as is suggested in [47]. Surprisingly, the maximum of correlation (less than the expected deflection angle by magnetic field) is not with center of these galaxies but at  $\sim 1.5R$  radius where one expects to be dominated by dark matter halo of the galaxy. Therefore the idea comes to mind that if there is a correlation, is it with the central AGNs or with dark matter halos around the galaxies? Unfortunately the present data is too scarce to permit any meaningful conclusion.

Close to uniform distribution of UHECRs events has been concluded to be the evidence that UHECRs originate from some extra-galactic astronomical objects and not from a decaying SDM in the Galactic Halo [55]. MACHOs observation [54] however shows that inner Halo has a heterogeneous composition and a precise modeling of the anisotropy must take into account the distribution of various components as well as the shape of the halo and nearby high densities [56].

The effect of magnetic field is also very important both in determination of composition and in the estimation of the amount of anisotropy. We have already mentioned that doublet and triplet clustering can be due to the magnetic field. Simulations show also that depending on the composition of the primaries, the anisotropy can be amplified (for heavy nuclei) or smeared (for protons) [57]. In addition, detailed investigation of present data shows that if AGASA and SUGAR estimation of flux is correct, potential extra-galactic nearby sources are not enough and a top-down source is needed [58].

### Exotic Candidates

List of non-classical (exotic) candidates and phenomena is much longer! Acceleration in conventional sources is limited to existence of a plasma and presence of a magnetic field. In exotic sources (or non-sources!) various microscopic or macroscopic processes can be the acceleration cause.

Evaporation of primordial black holes (PBH) is one of the suggested sources. The Hawking temperature at the end of black hole life is enough high to produce extremely energetic elementary particles like quarks and gluons and thus UHECRs [59]. Production models of PBH [60] however need fine-tuning and PBH evaporation effect on reionization constrains their present number density [61].

Topological defects were also a favorite potential source of UHECRs [62]. But following CMB anisotropy observations which have not found significant contribution from defects in the CMB power spectrum, the interest on them as the source of UHECRs is fading.

Many model makers have tried to overcome the constraint on the distance of charge particles as UHECR primaries by either assuming that they are neutrinos or by considering that the primary nucleons are produced by neutrino interaction in the galactic halo or nearby over-densities. Modification of neutrino-nucleon cross-section in models with large extra-dimensions [63] or extensions to SM make neutrinos as

possible primaries. These models increase neutrino-nucleon cross-section at high energies such that they can interact with terrestrial atmosphere and make UHECR showers. One problem with this class of models is that even if the cross-section of neutrino interaction becomes larger such that together with larger flux they can provide the observed flux of cosmic rays, one has to fine-tune the process such that it imitates a nucleon-nucleon interaction. The other problem specially regarding extra-dimensions is that UHECRs themselves strongly constrains the existence of low scale gravity and macroscopic extra-dimensions [64]. In addition, even in the case of existence of macroscopic extra-dimensions the smallness of interaction between bulk modes and fields on the visible brane prevents them to provide the observed flux of UHECRs [65].

Probably the most popular model with ultra high energy neutrinos is Z-burst model [66]. In this model it is assumed that neutrinos with energies  $\sim 10^{23}eV$  collide with a halo of neutrinos around Milky Way galaxy and create a hadronic jet which is observed as UHECRs. This model has various problems. Firstly it is very difficult to find a *conventional* source to accelerate charged particles to energies of order  $\sim 10^{23}eV$  which then they can make ultra high energy neutrinos. The second blow to this model is the upper limit on the mass of the neutrinos from WMAP [7] and neutrino oscillation experiments. In fact with a mass  $\lesssim 0.2eV$ , it has been shown that the amount of over-density of neutrinos around a halo of  $M \sim 10^{12}M_{\odot}$  is  $\lesssim 2$  [67]. Although there are claims that for masses as low as  $0.03eV$  this process can provide the observed flux, there are strong constraints on these models from amount of low energy  $\gamma$ -ray background they should make during interaction with presumed neutrino hale [68].

Violation of Lorentz invariance [69] due to quantum gravity effects which has been proposed for solving the puzzle of UHECRs is probably one of the most exotic suggestions. However, recent upper limits on the amount of Lorentz symmetry violation imposes strong constraints on this model [70].

Finally annihilation or decay of a superheavy dark matter particle is one the most popular non-conventional solutions. Existence of this class of particles was suggested long before the observation of UHECRs [71], but the quest of an explanation for unobserved GZK cutoff have given much more interest to search for particle models with necessary mass and lifetime. We first study the phenomenology of their decay and find constraints on their properties and other cosmological role they can play. Then in the last section of this chapter we briefly review some of suggested particle and production models.

### 1.3 Decay / Annihilation of SDM

To be the source of UHECRs, SDM - sometimes called  $X$  particles for simplicity - can be either meta stable with very small self-coupling [72] or self-annihilating stable particles [74]. Their interaction with other species is considered to be very small

and negligible. According to (1.1) for self-annihilating case the density variation is proportional to square of density. Therefore annihilation cross-section must be enough small such that a sufficient number of them survive the high density of the early universe or their density at that time must be very high. By contrast at present the annihilation cross-section must be enough large to explain the flux of UHECRs. These constraints and conditions which go to opposite directions impose some fine-tuning on SDM particle physics model and characteristics. In the case of decay however all the requests go to the same direction. The interaction of  $X$  with other particles must be very small. This decreases the probability of its production during preheating/reheating [75] and increases its lifetime. Therefore, we only have to find the right lifetime such that its decay corresponds to the observed flux of UHECRs. Here we only study the decay of SDM. Nonetheless, most of our results can also be applied to annihilation. One simply needs to find the corresponding annihilation cross-section (or rate) for a given lifetime.

Decay/annihilation of SDM have important implications for the evolution of high energy backgrounds. This can be used to constrain the mass and lifetime of these particles. A realistic estimation of these parameters however is not possible without considering in detail the energy dissipation of decay/annihilation remnants. If this reprocessing of high energy particles is not taken into account, the lifetime/annihilation rate must be many orders of magnitudes larger than the age of the Universe [73] [76] [78]. A more complete simulation of decay and dissipation [77] however shows that for the same mass range, the lifetime must be much shorter to explain the observed flux of UHECRs. This reduces the fine-tuning in the production mechanism. As we noted earlier, larger lifetime needs less interaction with other species and therefore it would be more difficult to make significant amount of  $X$  particle in the early universe.

### 1.3.1 Decay and Energy Dissipation

There is no theoretically rigorous motivation which restrict the possible mass range of SDM particles. The only constraint is that if their decay remnant should explain UHECRs, their mass can not be less than  $\sim 10^{21} \text{eV}$ . The absolute upper limit according to present believes in particle physics is the Planck mass i.e.  $\sim 10^{28} \text{eV}$ . Assuming that  $X$  particles must be related to physics at GUT scale i.e.  $\sim 10^{25} \text{eV}$  rather than Planck scale, we can reduce the upper limit to this value. The suggested range for the lifetime according to theories is also very large  $\tau_X \sim 10^{-3} - 10^{10} \tau$  where  $\tau_X$  and  $\tau$  are respectively the lifetime of  $X$  particles and the present age of the Universe [14] [79].

The decay or annihilation modes of SDM depends on their unknown particle physics model. If we assume that their self-annihilation probability is small, they can not have electric charge or any other charge with relatively strong coupling. It is also likely that they don't decay directly to SM particles and their decay has a number of intermediate unstable states which decay in their turn. It is also very

Table 1.2: Energy and multiplicity contribution in remnants of SDM.

Part.	$M_X = 10^{24} eV$		$M_X = 10^{22} eV$	
	Ener. %	Multi. %	Ener. %	Multi. %
$e^\pm$	$6.7 \times 2$	$9.7 \times 2$	$6.7 \times 2$	$9.8 \times 2$
$p^\pm$	$11.8 \times 2$	$1.4 \times 2$	$11.9 \times 2$	$1.4 \times 2$
$\nu \& \bar{\nu}$	$18.4 \times 2$	$28.3 \times 2$	$18.1 \times 2$	$28.3 \times 2$
$\gamma$	26.2	21	26.6	21

probable that remnants include stable WIMPs which are not easily observable [80]. To study the maximal effects of remnants on high energy backgrounds, we assume that at the end, the whole decayed energy goes to stable SM particles. Therefore the best guess for their decay is to assume that it looks like hadronic decay channel of a heavy neutral particle i.e.  $Z^0$  boson. Evidently it is not sure that they are bosons. But due to huge number of final particles after hadronization of primary partons, this does not significantly affect the decay remnants. To mimic the softening of energy spectrum due to multiple decay level, we assume that decay is similar to hadronization of a pair of gluon jets.

For simulating the fragmentation and hadronization of initial gluons we use PYTHIA program [81]. It can not however properly simulate ultra high energy events, not only because of unknown physics at  $10^{16} GeV$  scale, but also because of programming limits and it is necessary to extrapolate simulation results for  $E_{CM} \leq 10^{20} eV$  up to  $E_{CM} = 10^{24} eV$ . In the simulation all particles except  $e^\pm, p^\pm, \nu, \bar{\nu}$  and  $\gamma$  decay. This is a valid assumption when particles propagate in cosmological distances. We neglect neutrino mass and for simplicity we don't distinguish neutrino flavors in the final fragmentation. Contribution of stable species in the total multiplicity and the total decay energy is summarized in Table 1.2. It shows that the mass of SDM has little effect on the composition of remnants.

PYTHIA has been also used for determining the cross-section of interaction between remnants and the rest of baryonic contents of the Universe as well as CMB and other radiation backgrounds. For low energies ( $E \lesssim 4 GeV$ ) where PYTHIA does not work properly and for elastic scatterings measured or analytical calculation have been used. Details can be found in [77].

## 1.4 Cosmological Evolution

To obtain constraints on the mass and lifetime of SDM, one should determine the expected flux of high energy remnants of its decay on Earth and compare them with

observations. However, the lifetime and contribution of SDM particles in CDM are degenerate and one can increase one and decrease the other. For simplicity we assume that non-baryonic CDM consists only of SDM. When all other parameters (decay and fragmentation, etc.) are the same, this assumption leads to an upper limit on the lifetime of SDM.

Boltzmann equations for space-time and energy-momentum distribution of particles are [83]:

$$p^\mu \partial_\mu f^{(i)}(x, p) - (\Gamma_{\nu\rho}^\mu p^\nu p^\rho - e_i F_\nu^\mu p^\nu) \frac{\partial f^{(i)}}{\partial p^\mu} = -(\mathcal{A}(x, p) + \mathcal{B}(x, p)) f^{(i)}(x, p) + \mathcal{C}(x, p) + \mathcal{D}(x, p) + \mathcal{E}(x, p). \quad (1.3)$$

$$\mathcal{A}(x, p) = \Gamma_i p_i^\mu u_{i\mu} \quad u_{i\mu} \equiv \frac{p_{i\mu}}{m_i}. \quad (1.4)$$

$$\mathcal{B}(x, p) = \sum_j \frac{1}{(2\pi)^3 g_i} \int d\bar{p}_j f^{(j)}(x, p_j) A(s) \sigma_{ij}(s). \quad (1.5)$$

$$\mathcal{C}(x, p) = \sum_j \Gamma_j p_j^\mu u_{j\mu} \frac{1}{(2\pi)^3 g_i} \int d\bar{p}_j f^{(j)}(x, p_j) \frac{d\mathcal{M}^{(i)}_j}{d\bar{p}}. \quad (1.6)$$

$$\mathcal{D}(x, p) = \sum_{j,k} \frac{1}{(2\pi)^6 g_i} \int d\bar{p}_j d\bar{p}_k f^{(j)}(x, p_j) f^{(k)}(x, p_k) A(s) \frac{d\sigma_{j+k \rightarrow i+\dots}}{d\bar{p}}. \quad (1.7)$$

$x$  and  $p$  are coordinates and momentum 4-vectors;  $f^{(i)}(x, p)$  is the distribution of species  $i$ ;  $m_i$ ,  $e_i$  and  $\Gamma_i$ , are its mass, electric charge and width  $= 1/\tau_i$ ,  $\tau_i$  is its lifetime;  $\sigma_{ij}$  is the total interaction cross-section of species  $i$  with species  $j$  at fixed  $s$ . Expression:

$$\frac{d\sigma_{j+k \rightarrow i+\dots}}{d\bar{p}} = \frac{(2\pi)^3 E d\sigma}{g_i p^2 dp d\Omega} \quad (1.8)$$

is the Lorentz invariant differential cross-section of production of  $i$  in the interaction of  $j$  and  $k$ ;  $g_i$  is the number of internal degrees of freedom (e.g. spin, color);  $d\bar{p} = \frac{d^3 p}{E}$ . We treat interactions classically, i.e. we consider only two-body interactions and we neglect the interference between outgoing particles. It is a good approximation when the plasma is not degenerate. It is assumed that cross-sections include summation over internal degrees of freedom like spin;  $\frac{d\mathcal{M}^{(i)}_j}{d\bar{p}}$  is the differential multiplicity of species  $i$  in the decay of  $j$ ;  $\Gamma_{\nu\rho}^\mu$  is connection;  $F_\nu^\mu$  an external electromagnetic field; and finally  $\mathcal{E}(x, p)$  presents all other external sources.  $A(s)$  is a kinematic factor:

$$A(p_i, p_j) = ((p_i \cdot p_j)^2 - m_i^2 m_j^2)^{\frac{1}{2}} = \frac{1}{2} ((s - m_i^2 - m_j^2)^2 - 4m_i^2 m_j^2)^{\frac{1}{2}}. \quad (1.9)$$

where  $A\sigma$  presents the probability of an interaction.

Using cross-sections discussed in Sec.1.3.1, this system of equations along with Einstein equation can be solved numerically. The flux of high energy stable species



for a homogeneous cosmology is shown in Fig.1.1 and in Fig.1.2 the calculated flux for protons and photons has been compared with observations. The interesting conclusion (which was first noticed in [73]) but for a much longer lifetime) is that even for a relatively short lifetime of  $5\tau - 50\tau$  for which we have simulated the decay process, the observed flux of UHECRs is orders of magnitude higher than what a uniform distribution of SDM can provide. Therefore it is necessary to consider the effect of clumping of SDM in the galactic halo.

The simulation of halos even if we consider them to have a spherical symmetry is much more complicated than a homogeneous distribution. To simplify the task we simply consider a spatially limited halo with average over-density of  $\delta = 200$  i.e. equivalent to the over-density at virial radius. For a halo of mass  $M_H = 6 \times 10^{12} M_\odot$  the size of the virial radius is  $r_{200} \sim 120 kpc$  (for NFW profile [82]). We assume a total size of  $300 kpc$ . We consider two distribution for the baryonic matter. In the first case there is no segregation between baryonic and non-baryonic matter. However the result of MACHOs observations show that it is possible that the inner 20 kpc of the halo is dominated by baryonic dark matter. Therefore in the second case we consider such a situation. Results for protons and photons is shown in Fig.1.3.

According to this plot, the effect of clumping is more significant for protons than for photon which are more sensitive to the presence of an inner baryonic matter. If the decay pattern we have considered here is realistic, the lifetime of SDM is close to  $50\tau$ . Considering the uncertainties in determination of fluxes and in the simulation, one can conclude that present data is compatible with a mass  $m_X \sim 10^{22} eV - 10^{24}$  and a lifetime  $\tau_X \sim 10\tau - 100\tau$ . Our results are also consistent with the latest upper limit on the flux of high energy neutrino from Lake Baikal experiment [88]. Nonetheless complex and mostly unknown physics of neutrinos reduces the reliability of high energy neutrino constraints.

### 1.4.1 Constraints from Other Cosmological Data

Before concluding this section we discuss some of other observable consequences of a decaying SDM and constraints they put on the parameter space of SDM models.

A relatively short living SDM can distort CMB. This issue has been studied and constrained after recent WMAP observation of CMB anisotropy [87]. Their constraints from WMAP spectrum of CMB are based on the modification of equation of state of the Universe (see next section) without considering the energy dissipation of remnant. The lower limit on the lifetime of SDM at 95.4% *C.L.* is  $\tau_X \gtrsim 52 Gyr \approx 4\tau$  and at 68% *C.L.*,  $\tau_X \gtrsim 123 Gyr \approx 9\tau$ . These results even without considering the energy dissipation are compatible with the simulation discussed in the previous section and our constraints are even somehow more stringent than what obtained in [87].

In fact we have also calculated the distortion due to SDM decay for a homogeneous universe. Fig.1.4 shows the relative distortion of photon background around

CMB energy for a homogeneous universe dominated by SDM with respect to a stable dark matter. The distortion around maximum of CMB spectrum is very small, less than 1 to  $10^8$  parts for  $E \lesssim 3eV$ . The exact numerical values however depends somehow on the cross-section cuts at low energies. Nevertheless, the contribution of SDM remnants at low energies close to maximum of the CMB spectrum is much smaller than other foreground sources like galaxies and galaxy clusters. The study of distortion in CMB anisotropy is more complicated. A simple estimation can be obtained by multiplying the uniform distortion by an average over-density. For an over-density of order  $\sim 100$  at the scale of clusters, the expected distortion at small angle (large  $l$ ) is  $\lesssim 10^{-6}$ , much smaller than resolution of present and near future CMB anisotropy experiments.

The other important cosmological constraint is the increase in the entropy due to changing of CDM to Hot Dark Matter (HDM). Our simulation shows that the increase in the entropy of electrons, protons and photons are completely negligible. There is a small increase in  $e^+$  and  $p^-$  entropy, but much smaller than the total entropy of the Universe and compatible with observations.

As the mass scale of SDM is expected to be close to GUT scale, it has been suggested [89] [37] that their decay may be able to generate additional baryon and lepton asymmetry. The rate of baryonic (or leptonic) number production by decay of SDM in comoving frame can be expressed as:

$$\frac{d(n_b - n_{\bar{b}})}{dt} + 3\frac{\dot{a}(t)}{a(t)}(n_b - n_{\bar{b}}) = \frac{\varepsilon n_{dm}}{\tau}. \quad (1.10)$$

where  $\varepsilon$  is the total baryon number violation per decay. The solution of this equation is:

$$\Delta(n_b - n_{\bar{b}}) = \varepsilon n_{dm}(t_0) \left(1 - \exp\left(-\frac{t - t_0}{\tau}\right)\right) \frac{(1 + z_0)^3}{(1 + z)^3}. \quad (1.11)$$

$$\Delta B \equiv \frac{\Delta(n_b - n_{\bar{b}})}{2g_* n_\gamma} = \frac{\varepsilon n_{dm}(t_0)}{2g_* n_\gamma(t_0)} \left(1 - \exp\left(-\frac{t - t_0}{\tau}\right)\right) \frac{(1 + z)}{(1 + z_0)}. \quad (1.12)$$

If  $t_0 = t_{dec}$ ,  $\frac{n_{dm}(t_0)}{n_\gamma(t_0)} \sim 10^{-22}$  (for  $m_{dm} = 10^{24}eV$ ). Therefore  $\Delta B \sim 10^{-22}\varepsilon$  at  $z = 0$ . As  $\varepsilon$  can not be larger than total multiplicity,  $\sim 1000$ ,  $\Delta B \lesssim 10^{-19}$ , i.e. much smaller than primordial value  $\sim 10^{-10}$ . For  $\varepsilon = 0.1$  at all energies,  $\varepsilon_{tot} = 0.1\mathcal{M}_{tot}$ . This leads to a smaller  $n_{\bar{p}}$  i.e. larger total baryonic number, but the change is very small. The same is true for leptonic number, but energy density of leptons with respect to anti-leptons increases by an amount comparable to  $\varepsilon$ .

## 1.5 Equation of State of the Universe

We continue the odyssey of a superheavy dark matter by considering its signature on one of the hottest and most mysterious topics of physics and cosmology today: the Equation of State of the Universe (ESU).

Here we show that the decay of dark matter has an effect very similar to dark energy. In fact it is easy to see the reason crudely. Assuming that the decay remnants stay relativistic, cosmological evolution equation close to present time is:

$$H^2 = \frac{8\pi G}{3} \left( \rho_X(t_0) \frac{a_0^3}{a^3} + \rho_X(t_0) \frac{a_0^4}{a^4} (1 - e^{-\frac{(t-t_0)}{\tau_X}}) + e^{-\frac{(t-t_0)}{\tau_X}} + \rho_{hot} + \rho_q \right) \quad (1.13)$$

where  $\rho$  indicates the density and from now on the subscript  $q$  is used for quintessence. In this section we assume that quintessence term is a cosmological constant. Time  $t_0$  is an arbitrary initial time. Equation (1.13) should be compared with the evolution equation for a cosmology with a stable DM:

$$H^2 = \frac{8\pi G}{3} \left( \rho_X(t_0) \frac{a_0^3}{a^3} + \rho_{hot} + \rho_q \right) \quad (1.14)$$

If  $t - t_0 \ll \tau_X$  and the first cosmology is treated as the second, the observer find a slightly smaller density for DM but a growing dark energy i.e.  $w_q \lesssim -1$  where  $w_q$  determines the equation of state defined as:

$$P = w\rho \quad (1.15)$$

$P$  is pressure. For dark matter  $w = 0$ , for hot matter  $w = 1/3$  and for a cosmological constant  $w = -1$ . A more detailed proof can be found in [90].

Fig.1.5 shows the evolution of  $\rho(z)$  the density of CDM+HDM at low and medium redshifts in a flat universe with and without a cosmological constant and when DM is stable or it is decaying. As expected, the effect of SDM decay is more significant in a matter dominated universe i.e. when  $\Lambda = 0$ . For a given cosmology, the lifetime of SDM is the only parameter that significantly affects the evolution of  $\rho$  and the difference between models with  $M_X = 10^{12}eV$  and  $M_X = 10^{24}eV$  is only  $\approx 0.4\%$ . Consequently, in the following we neglect the effect of DM mass. We have tried [90] to see if we can find the finger print of a decaying SDM in SN Type-Ia data which is the most direct way to study the equation of state of the Universe [15] [16]. The measurement is based on observation of maximum apparent magnitude of SN Type-Ia's light-curve. After correction for various observational and intrinsic variations like K-correction, width-luminosity relation, metalicity, reddening and Galactic extinction, it is assumed that their magnitude is universal. The difference in apparent magnitudes of SNs is then only related to difference in distance and consequently to cosmological parameters. The apparent magnitude of an object  $m(z)$  is related to its absolute magnitude  $M$ :

$$m(z) = M + 25 + 5 \log D_L \quad (1.16)$$

where  $D_L$  is the Hubble-constant-free luminosity distance:

$$D_L = \frac{(z+1)}{\sqrt{|\Omega_R|}} \mathcal{S} \left( \sqrt{|\Omega_R|} \int_0^z \frac{dz'}{E(z')} \right) \quad (1.17)$$

$$\mathcal{S}(x) = \begin{cases} \sinh(x) & \Omega_R > 0, \\ x & \Omega_R = 0, \\ \sin(x) & \Omega_R < 0. \end{cases}$$

$$E(z) = \frac{H(z)}{H_0}. \quad (1.18)$$

$$H^2(z) = \frac{8\pi G}{3} T^{00}(z) + \frac{\Lambda}{3}. \quad (1.19)$$

In (1.19) we used energy-momentum tensor in place of  $\rho$  to distinguish between ideal gas approximation and the general case where matter components are in interaction and their distribution is not necessarily thermal. This is the case when DM decays at late time and the distribution of remnants remains non-thermal. We restrict fits to flat Cosmologies and fit cosmological models to published high redshift SN observations. Cosmological models with and without Cosmological Constant and stable or decaying DM are fitted to the data. We use minimum- $\chi^2$  method for fitting. Universal absolute magnitude  $M$  is considered as a free parameter and  $\chi^2$  of each model is minimized with respect to it. Following aprioris are applied to the present density of dark energy:

$$2.38 \times 10^{-11} \leq \rho_\Lambda \equiv \frac{\Lambda}{8\pi G} \leq 3.17 \times 10^{-11} eV^4 \quad (1.20)$$

We use  $\rho_\Lambda$  rather than  $\Omega_\Lambda$  because the latter depends on the equation of state and lifetime of the dark matter. The range of  $\rho_\Lambda$  given here is equivalent to  $0.6 \leq \Omega_\Lambda^{eq} \leq 0.8$  for a stable CDM and  $H_0 = 70 \text{ km Mpc}^{-1} \text{ sec}^{-1}$  (This is the value used as initial input to the simulation of SDM decay (See [77] for details of initial conditions). We use  $\Omega_\Lambda^{eq}$  notation to distinguish between this quantity which is obtained from simulation using (1.19) and the input  $\Omega_\Lambda = \Lambda/3H_0^2$ .

Fig.1.6 shows the residues of the best fit to SDM simulation. Although up to  $1\text{-}\sigma$  uncertainty all models with stable or decaying DM with  $5\tau \lesssim \tau_X \lesssim 50\tau$  and  $0.68 \lesssim \Omega_\Lambda^{eq} \lesssim 0.72$  are compatible with the data, a decaying DM with  $\tau_X \sim 5\tau$  systematically fits the data better than stable DM with the same  $\Omega_\Lambda$ . Models with  $\Lambda = 0$  are ruled out with more than 99% confidence level.

In fitting the results of DM decay simulation to the data we have directly used the equation (1.19) without defining any analytical form for the evolution of  $T^{00}(z)$ . To be able to compare our results directly with other works, we have also fitted an analytical model to the simulation. It includes a stable DM and a quintessence matter. Its evolution equation is:

$$H^2(z) = \frac{8\pi G}{3} (T_{st}^{00} + \Omega_q(z+1)^{3(w_q+1)}). \quad (1.21)$$

The term  $T_{st}^{00}$  is obtained from our simulation when DM is stable. In addition to CDM, it includes a small contribution from hot components i.e CMB and relic

Table 1.3: Cosmological parameters from simulation of a decaying DM and parameters of the equivalent quintessence model.  $H_0$  is in  $km\ Mpc^{-1}\ sec^{-1}$  and correspond to  $H_0$  after fitting matter and quintessence densities.

	Stable DM			$\tau_X = 50\tau$			$\tau_X = 5\tau$		
$\Omega_\Lambda$	0.68	0.7	0.72	0.68	0.7	0.72	0.68	0.7	0.72
$H_0$	69.953	69.951	69.949	69.779	69.789	69.801	68.301	68.415	68.550
$\Omega_\Lambda^{eq}$	0.681	0.701	0.721	0.684	0.704	0.724	0.714	0.733	0.751
$\Omega_q$	-	-	-	0.679	0.700	0.720	0.667	0.689	0.711
$w_q$	-	-	-	-1.0066	-1.0060	-1.0055	-1.0732	-1.0658	-1.0590
$\chi^2$	62.36	62.23	62.21	62.34	62.22	62.21	62.22	62.15	62.20

neutrinos. Therefore in this model all the effects of a decaying DM is encapsulated in the quintessence model. The time/redshift variation of dark energy is thus due to decaying DM. For a given  $\Omega_\Lambda$  and  $\tau$ , the quintessence term is fitted to:

$$T^{00} - T_{st}^{00} + \frac{\Lambda}{8\pi G} \quad (1.22)$$

Note that the exact equivalent model is:

$$H^2(z) = \frac{8\pi G}{3}((1 - \Omega_q)(z + 1)^3 + \Omega_q(z + 1)^{3(w_q+1)}). \quad (1.23)$$

However, because (1.23) depends only on one density, the minimization of  $\chi^2$  of the fit in this model have a trivial solution with  $w_q = -1$ ,  $\Omega_q = \Omega_\Lambda$ . Non-trivial solutions depend on both  $w_q$  and  $\Omega_q$  which are degenerate with infinite number of solutions. The model we have used here generates a very good equivalent model to SDM with less than 2% error, but because CDM and quintessence terms are not fitted together,  $\Omega$  is not exactly 1.

Parameters of models in the 1- $\sigma$  distance of the best fit are summarized in Table 1.3. The results for  $\tau_X = 5\tau$  models are surprisingly close to the results obtained recently by fitting the best SN light-curves observed by HST [91]. Unfortunately the errors of both fits are too large to make any definitive conclusion. Nevertheless, there is very small chance that closeness of mean values be just accidental. The lifetime for the best-fit models is somehow smaller than the lower limit we found in Sec.1.4. However, one should not forget that hadronization we have considered is maximal. i.e. we have considered that all the remnants of the decay of SDM is visible and has the same baryonic fraction as low energy hadronization. If part of

the remnants consist of a lighter dark matter e.g. LSP (neutralino) the lower limit on the lifetime decreases.

Conclusion we can make from this section is that there is probably a finger print of a decaying dark matter in the present data. Evidently this is not the only model which can explain a  $w_q \lesssim -1$ . But most other models need a fine-tuning. They have either unconventional kinetic terms [92] or a negative potential which in the context of SUSY models (before breaking) can not be obtained, or unconventional equation of state like a Chaplygin Gas [93]. Other scalar field models with multiple-field contents or what is called a phantom matter which has a negative kinetic energy have been also suggested [94] [95].

## 1.6 Quintessence

Up to now we used cosmologies with a dark energy (or Cosmological Constant) without talking about the nature of this mysterious term in Einstein equation (For review see [97] and references therein).

Cosmological Constant has been added by Einstein to his equation to be able to have a static solution (For a historical review see [96]). Later however, it was proved by Friedmann that this solution is unstable [98]. George Gamov has written that he once heard from Einstein to call Cosmological Constant his *greatest blunder*. But in a letter to Einstein, Lemaître says that it is a genius idea and interprets it as being the *Vacuum Energy*. This name is the origin of a significant confusion and many speculations and doubts even today. We come back to this point later. In their famous book *Gravitation*, Misner, Thorne and Wheeler call it *Pandora Box* and consider it only exceptionally.

Today we know that Cosmological Constant or dark energy is the dominant contents of the Universe. According to SN data:  $\Omega_{\Lambda} = 0.75^{+0.07}_{-0.06}$  [91], and from CMB anisotropy measurement:  $\Omega_{\Lambda} \approx 0.73$ . In a universe very close to flat this means that dark energy contribution is more than 70% of the total energy contents of the Universe. However, as the density of DE had barely changed presumably since after inflation, this means that at that time its value was  $\sim 10^{45}$  to  $\sim 10^{100}$  times (depending on inflation scale) smaller than matter density. Such a small value became nonetheless dominant after galaxy formation, a good luck for us, otherwise perturbations couldn't grow to make structures we see in present Universe including ourselves. The situation is worth if the origin of Cosmological Constant is related to quantum gravity. For instance if it is the vacuum expectation value of a quantity at quantum gravity scale - as Lemaître suggested - its natural value should be  $\sim M_p^4 \approx 10^{112} \text{eV}^4$ , i.e.  $\sim 10^{123}$  times larger than observed value. The unexpectedly small value of Cosmological Constant - if Lemaître interpretation is correct - is called first cosmological constant problem. The fine-tuning such that it become dominant only after galaxy formation is called second cosmological constant or coincidence problem (see [97] and references therein).

The first problem can be solved or softened if dark energy is not vacuum energy but comes from another form of matter. This idea is the basis for most of suggested models. A reasonable solution for the second problem logically seems to be a direct relation between dark matter and dark energy such that somehow they control each other and what we consider to be a *coincidence* is something inherent to the nature of these entities.

A number of dark energy models have been made based on this line of thinking. In [99] a matter component with smooth equation of state i.e  $w_q \sim -0.3$  and dependence on the total energy has been proposed. Another possibility is an interaction between dark matter and dark energy. Various type of interactions have been investigated. one of them is an asymptotic scaling law between density of DE and DM. In this model due to a dissipative interaction between dark matter and quintessence scalar field  $\phi_q$ , the relative density of dark matter and dark energy  $\rho_{CDM}/\rho_q$  approaches a constant value [100] [101] [102]. A class of potentials  $V_q(\phi_q)$  have been found such that the equation of state have a solution satisfying this *strong coincidence scaling* [100]. Constraints on this model from nucleosynthesis, leads to  $w_q \gtrsim -0.7$  which is only marginally compatible with WMAP data and far from publicly available SN-Ia data which prefers  $w_q \sim -1$ .

Interaction between DM and DE have been extensively studied in the context of traditional quintessence models with tracking solutions and  $w_q > -1$  [103]. It has been shown that these models have lagrangians equivalent to Brans-Dicke lagrangian with power law potential and consequently behave like a *Fifth Force*. Modification of the CMB anisotropy spectra by such interactions is observable and put stringent constraints on their parameters.

Models with a time dependent DM mass due to interaction between quintessence scalar and dark matter have been also considered [104]. Coupling between two fields in this class of models increases the parameter space for both and reduces by orders of magnitudes the amount of fine tuning. However, there are strong limits on the variation of fundamental parameters including DM mass. Moreover, in these models the largest amount of variation happens around and after matter domination epoch. Consequently the mass variation must leave an imprint on the CMB and large structure formation which has not been observed.

Most quintessence models suffer also from difficulties regarding particle physics model for the quintessence scalar field with proper mass [105]. Quintessence field is usually considered to be an axion-like particle with high-order, non-renormalizable interactions with SM (or its super-symmetric extension) fields. However, any supergravity induced interaction between  $\phi_q$  and other scalars with VEV of the order of Planck mass can increase the very tiny mass of the  $\phi_q$  - in most models  $m_q \sim H_0 \sim 10^{-33} eV$  - unless a discrete global symmetry prevents their contribution to the mass [106](see also [20] for some solutions for this problem). In summary no ideal solution for coincidence problem has yet been found.

In this section we describe a model for the dark energy somehow different from

previous quintessence models [107]. We assume that DE is the result of condensation of a scalar field produced during very slow decay of the superheavy dark matter which we have studied in the previous sections. In traditional quintessence models the scalar field is produced during inflation or reheating period in large amount such that for controlling its contribution to the total energy of the Universe today, its potential must be decreasing since that time. Usually the potential is a negative exponential, sum of two exponentials, or a negative power polynomial function and their parameters must be somehow fine-tuned [105]. In the present model very small production rate of the scalar field due to very small decay rate of SDM replaces the fine-tuning of the potential and practically any scalar field even without a self-interaction has a tracking solution for a large part of its parameter space. We will see that soon after production of SDM,  $\phi_q$  behaves like a cosmological constant without need for fine-tuning of parameters. As we have seen in the previous section, subsequently the decay of SDM imitates a universe with a quintessence field for which  $w_q$  is slightly smaller than  $-1$ . This is exactly what has been observed ! Another advantage of this model is that there would not be any future horizon because one day SDM will completely decay and automatically changes the equation of state of the quintessence field. The existence of a future horizon in an accelerating universe is problematic because some particle physics models specially string theory lack a well defined vacuum in a de Sitter space with future horizon. We also show that large mass and lifetime of SDM is crucial for making this model a proper quintessence model.

What we present here is based on the assumption that late time decoherence of quintessence field is possible. It has been shown in case of inflaton that decoherence is only possible for modes with a wavelength larger than horizon. This put an upper limit on the mass of the quintessence, later the decoherence time, smaller the mass upper limit. If SDM is produced during preheating [108] just after the end of the inflation presumably at scales  $\sim 10^{14}eV - 10^{16}eV$  which correspond to:

$$H \sim 10^{-6}eV - 10^{-4}eV \quad (1.24)$$

the permitted mass range is  $m_q \lesssim 10^{-6}eV$  [109] [110]. When the size of the Universe get larger,  $\phi_q$  stops decohering. This also helps having a very small dark energy density. If the preheating/reheating had happened when the Hubble Constant was smaller, then  $m_q$  also must be smaller to have long wavelength modes which can decohere. The issue of decoherence is very complex and needs more investigation.

### 1.6.1 Co-Evolution of Decaying SDM and Quintessence Field

Consider that just after inflation among the field contents of the Universe there is  $\phi_x$  a superheavy, meta-stable dark matter (SDM) which decouples from the rest of the *primordial soup* since very early time. These are the same properties we assumed for  $X$  particles in the previous sections. We don't consider other fields in detail. The



only constraint on the other fields is that they must consist of light species including baryons, neutrinos, photons, and light dark matter - by light we mean with respect to  $X$ . For simplicity we assume that  $X$  is a scalar field  $\phi_x$ . If  $\phi_x$  is a spinor or vector the general conclusions presented here does not change. A very small part of  $\phi_x$  decay remnants is considered to be a scalar field  $\phi_q$  with negligibly weak interaction with other fields.

The effective lagrangian can be written as:

$$\mathcal{L} = \int d^4x \sqrt{-g} \left[ \frac{1}{2} g^{\mu\nu} \partial_\mu \phi_x \partial_\nu \phi_x + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi_q \partial_\nu \phi_q - V(\phi_x, \phi_q, J) \right] + \mathcal{L}_J \quad (1.25)$$

The field  $J$  presents collectively other fields. The term  $V(\phi_x, \phi_q, J)$  includes all interactions including self-interaction potential for  $\phi_x$  and  $\phi_q$ :

$$V(\phi_x, \phi_q, J) = V_q(\phi_q) + V_x(\phi_x) + g \phi_x^m \phi_q^n + W(\phi_x, \phi_q, J) \quad (1.26)$$

The term  $g \phi_x^m \phi_q^n$  is important because it is responsible for annihilation of  $X$  and back reaction of quintessence field to SDM.  $W(\phi_x, \phi_q, J)$  presents interactions which contribute to the decay of  $X$  to light fields and to  $\phi_q$  (in addition to what is shown explicitly in (1.26)). The very long lifetime of  $X$  constrains this term and  $g$ . They must be strongly suppressed. For  $n = 2$  and  $m = 2$  the term proportional to  $g$  contributes to the mass of  $\phi_x$  and  $\phi_q$ . Because of the huge mass of  $\phi_x$  (which must come from another coupling) and its very small occupation number, we can use classical limit i.e.  $\langle \phi_x^2 \rangle \sim 2\rho_x/m_x^2$ . For sufficiently small  $g$ , the effect of this term on the mass of the SDM is very small. We discuss the rôle of this term in detail later. If the interaction of other fields with  $\phi_q$  is only through the exchange of  $X$  (for instance due to a conserved symmetry shared by both), the huge mass of  $X$  suppresses the interaction and therefore the modification of  $m_q$ . If  $X$  is a spinor, the lowest order (Yukawa) interaction term in (1.25) is  $g \phi_q \bar{\psi} \psi$ . In the classical treatment of  $X$ :

$$\bar{\psi} \psi \sim \frac{\rho_x}{m_x} \quad (1.27)$$

The lagrangian (1.25) leads to following system of equations for the fields:

$$\dot{\phi}_q [\ddot{\phi}_q + 3H\dot{\phi}_q + m_q^2 \phi_q + \lambda \phi_q^3] = -2g\dot{\phi}_q \phi_q \left( \frac{2\rho_x}{m_x^2} \right) + \Gamma_q \rho_x \quad (1.28)$$

$$\dot{\rho}_x + 3H\rho_x = -(\Gamma_q + \Gamma_J)\rho_x - \pi^4 g^2 \left( \frac{\rho_x^2}{m_x^3} - \frac{\rho_q^2}{m_q^3} \right) \quad (1.29)$$

$$\dot{\rho}_J + 3H(\rho_J + P_J) = \Gamma_J \rho_x \quad (1.30)$$

$$H^2 \equiv \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} (\rho_x + \rho_J + \rho_q) \quad (1.31)$$

$$\rho_q = \frac{1}{2} m_q^2 \dot{\phi}_q^2 + \frac{1}{2} m_q^2 \phi_q^2 + \frac{\lambda}{4} \phi_q^4 \quad (1.32)$$

Eq. (1.29) is Boltzmann equation for  $X$  particles and its right hand sides can be obtained from detail calculation of its annihilation and reproduction due to term  $g\phi_x^2\phi_q^2$  in the lagrangian [107].  $\rho_q'$  is the density of quintessence particles (not the classical field  $\phi_q$ ) with an average energy larger than  $m_x$  in the local inertial frame. Only interaction between these particles contribute to the reproduction of SDM.  $\Gamma_q$  and  $\Gamma_J$  are respectively the decay width of  $X$  to  $\phi_q$  and to other species. The effect of decay lagrangian  $W(\phi_x, \phi_q, J)$  appears as  $(\Gamma_q + \Gamma_J)\rho_x$  which is the decay rate of  $X$  particles.

At very high temperatures when  $\rho_x \gg \pi^4 g^2 m_x^3 \Gamma$ , the annihilation and reproduction terms in (1.29) are dominant.  $X$  particles however are non-relativistic up to temperatures close to their rest mass. Quintessence scalar particles at this time are relativistic and therefore their density falls faster than SDM density by a factor of  $a(t)$ . The probability of self-annihilation also decreases very rapidly. Consequently, from very early time only the decay term in (1.29) is important. The dominance of annihilation/reproduction can happen only if the production temperature of  $X$  particles i.e. preheating/reheating temperature is very high. Such scenarios however can make dangerous amount of gravitinos [111]. A lower reheat temperature does not however compromise the production of SDM because it has been shown [112] that even with a very low reheating temperature they can be produced. Another reason for this simplification is that we are interested in the decohered modes of  $\phi_q$ . Self-annihilation of  $X$  particles makes  $\phi_q$  particles which are highly relativistic and don't participate in the condensate modes.

Equations (1.28) to (1.32) are highly non-linear and coupled. There are however two asymptotic regimes which permit an approximate analytical treatment. The first one happens very early just after production of  $X$  particles presumably after preheating [113] [108] and decoherence of  $\phi_q$ 's long wavelength modes. In this epoch  $\phi_q \sim 0$  and can be neglected. The other regime is when comoving time variation of  $\phi_q$  is very slow and one can neglect  $\ddot{\phi}_q$ . We show that the first regime leads to a saturation (tracking) solution where  $\phi_q \rightarrow cte$ . It then can be treated as the initial condition for the second regime when  $\phi_q$  changes slowly.

Neglecting the last term in the right hand side of (1.29), this equation has a straightforward solution:

$$\rho_x(t) = \rho_x(t_0) e^{-\Gamma(t-t_0)} \left( \frac{a(t_0)}{a(t)} \right)^3 \quad (1.33)$$

where  $\Gamma \equiv \Gamma_q + \Gamma_J$  is the total decay width of  $X$ . Initial time  $t_0$  is considered to be after production and decoupling of  $X$ . After inserting the solution (1.33) and neglecting all the terms proportional to  $\phi_q$ , equation (1.28) can be solved:

$$\frac{1}{2} \dot{\phi}_q^2(t) \equiv K_q(t) = \left( \frac{a(t_0)}{a(t)} \right)^6 \left[ K_q(t_0) + \Gamma_q \rho_x(t_0) \int_{t_0}^t dt \frac{a^3}{a(t_0)} e^{-\Gamma(t-t_0)} \right] \quad (1.34)$$

For  $a \propto t^k$  the integral term in (1.34) decreases with time (i.e.  $\ddot{\phi}_q < 0$ ). This means that after a relatively short time  $\phi_q$  is saturated and its density does not

change, in other words it behaves like a cosmological constant. Due to quantum effects the initial value of  $K_q(t_0)$  is positive. Its exact value can only be determined by investigating the process of decoherence of  $\phi_q$ . Because of  $a^{-6}(t)$  factor in (1.34) however, with the expansion of the Universe the effect of this term on  $\dot{\phi}_q$  decreases very rapidly.

During the second regime when  $\phi_q$  changes very slowly, we can neglect  $\ddot{\phi}_q$  and higher orders of  $\dot{\phi}_q$ . Equation (1.28) thus simplifies to:

$$\dot{\phi}_q(m_q^2\phi_q + \lambda\phi_q^3) = -2g\dot{\phi}_q\phi_q\left(\frac{2\rho_x}{m_x^2}\right) + \Gamma_q\rho_x \quad (1.35)$$

We expect that self-interaction of  $\phi_q$  be much stronger than its coupling to  $X$ . Neglecting the first term in the right hand side of (1.35), its  $\phi_q$ -dependent part can be integrated:

$$\frac{d}{dt}\left(\frac{1}{2}m_q^2\phi_q^2 + \frac{\lambda}{4}\phi_q^4\right) = \frac{dV}{dt}(\phi_q) = \Gamma_q\rho_x \quad (1.36)$$

and solved:

$$V_q(\phi_q) = V_q(\phi_q(t'_0)) + \Gamma_q\rho_x(t'_0) \int_{t'_0}^t dt \left(\frac{a(t'_0)}{a(t)}\right)^3 e^{-\Gamma(t-t'_0)} \quad (1.37)$$

Here  $V_q$  is the potential energy of  $\phi_q$ . From (1.36) and (1.37) it is clear that the final value of the potential and therefore  $\phi_q$  energy density is driven by the decay term and not by self-interaction. Therefore the only vital condition for this model is the existence of a long life SDM and not the potential of  $\phi_q$ . This is very different from most quintessence models. In [114] also a  $\phi^4$  potential has been used in the context of hybrid scalar models. In this model the dark matter is also a condensed scalar.

In (1.37) the initial values  $t'_0$  and  $\phi_q(t'_0)$  correspond respectively to time and to  $\phi_q$  in the first regime when it approaches to saturation. Similar to (1.34), the time dependence of  $\phi_q$  in (1.37) vanishes exponentially and the behavior of  $\phi_q$  approaches to a cosmological constant.

Assuming  $a(t) \propto t^k$  and  $t_s - t'_0 \ll 1/\Gamma$  where  $t_s$  is the saturation time, we find:

$$V(\phi_q) - V(\phi_q(t'_0)) \sim \frac{\Gamma_q\rho_x(t'_0)}{(3k-1)} \left(1 - \left(\frac{t'_0}{t}\right)^{(3k-1)}\right). \quad (1.38)$$

Defining saturation time as the time when  $V(\phi_q) - V(\phi_q(t'_0))$  has 90% of its final value, if  $t_s \ll t_{eq}$  with  $t_{eq}$  the matter-radiation equilibrium time,  $k = 1/2$  and:

$$t_s \sim 100t'_0 \quad (1.39)$$

For  $t_s \gg t_{eq}$ ,  $k = 2/3$  and:

$$t_s \sim 10t'_0 \quad (1.40)$$

### 1.6.2 Numerical Solution

A better understanding of the behavior and the parameter space of this model needs numerical solution of equations (1.28) to (1.32). We have also added the interaction between various species of the Standard Model (SM) particles as explained in Sec.1.3.1 to the simulation to be closer to the real cosmological evolution and to obtain the equation of state of the remnants. We try a number of combination of parameters to find how sensitive is the behavior of the quintessence field  $\phi_q$ . Parameter space is however degenerate and two models lead to very similar results for the quintessence field if:

$$\frac{f_q}{f'_q} = \frac{z'\Gamma'm_x}{z\Gamma m'_x} \quad (1.41)$$

This helps to extend the conclusion to the part of the parameter space which is not accessible due to limitations of the numerical simulation. For the lifetime of  $X$  we use  $\tau_X = 5\tau - 50\tau$ , similar to Sec.1.3.1. Results presented here belong to  $\tau_X = 5$ . Our test shows that increasing  $\tau_X$  to  $50\tau$  does not significantly modifies the main characteristics of dark energy (for more detail see [107]).

Fig.1.7 shows the evolution of  $\phi_q$ , its time derivative and its total energy density from the end of  $X$  production to saturation redshift  $z_s$ . Here we have used as  $z_s$  the redshift after which up to simulation precision the total energy density of  $\phi_q$  does not change anymore. The result is consistent with the approximate solutions discussed earlier. The final density of  $\phi_q$  is practically proportional to  $\Gamma_q/\Gamma$  which encompasses 3 important parameters of the model: The fraction of energy of the remnants which changes to  $\phi_q$ , the fraction of energy in the long wavelength modes which can decohere and the coupling of these modes to the environment which contributes to  $\phi_q$  yield and to the formation redshift of the classical quintessence field  $\phi_q$ . Therefore the effective volume of the parameter space presented by this simulation is much larger and the fine-tuning of parameters are much less than what is expected from just one parameter.

Fig.1.8 shows the evolution in the contribution of different terms of the lagrangian (1.25) to the total energy of  $\phi_q$ . Very soon after beginning of quintessence field production the potential takes over the kinetic energy and the latter begins to decrease. The relative contribution of each term and their time of dominance, as this figure demonstrates, depends on the model parameters specially on  $m_q$  and  $\lambda$ . This plot shows also that changing parameters by orders of magnitude does not change the general behavior of the model significantly and for a large part of the parameter space the final density of quintessence energy is close to the observed value. This can also be seen in Fig.1.9 and Fig.1.10 where the evolution of quintessence energy is shown for various combination of parameters.

### 1.6.3 Perturbations

Observations show that the dark energy is smooth and uncorrelated from the clumpy dark matter [17]. If its origin is the decay of the dark matter, the question arises whether it clumps around dark matter halos or has a large scale perturbation which is not observed in the present data. We show here that due to special characteristics of SDM,  $\phi_q$  perturbations are very small.

We use the synchronous gauge metric:

$$ds^2 = dt^2 - a^2(t)(\delta_{ij} - h_{ij})dx^i dx^j \quad (1.42)$$

For small spatial fluctuations  $\phi_q(x, t) = \bar{\phi}_q(t) + \delta\phi_q(x, t)$  where from now on barred quantities are the homogeneous component of the field depending only on  $t$ . We define the same decomposition for other fields.

We consider only scalar metric fluctuations  $h \equiv \delta^{ij}h_{ij}$  and neglect other components. Evolution equation for  $h$  is:

$$\frac{1}{2}\ddot{h} + \frac{\dot{a}}{a}\dot{h} = 4\pi G(4\dot{\phi}_q\delta\dot{\phi}_q - 2\delta V(\phi_q, \rho_x) + \delta\rho_x + \delta\rho_J + 3\delta P_J) \quad (1.43)$$

where  $\delta\rho_x$  is the fluctuation of  $X$  particles density,  $\delta\rho_J$  and  $\delta P_J$  are respectively the collective density and pressure fluctuation of other fields. From the lagrangian (1.25), the dynamic equation of  $\phi_q$  is:

$$\partial_\mu(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi_q) + \sqrt{-g}V'(\phi_q, \phi_x, J) = 0 \quad (1.44)$$

This equation and the energy momentum conservation determine the evolution of  $\delta\phi_q(x, t)$ :

$$\begin{aligned} & \dot{\phi}_q \left[ \delta\ddot{\phi}_q + \partial_i\partial^i(\delta\phi_q) + V_q''(\bar{\phi}_q)\delta\phi_q + 2g\left(\frac{2\bar{\rho}_x}{m_x^2}\right)\delta\phi_q + 3\frac{\dot{a}}{a}\delta\dot{\phi}_q \right] + \\ & \frac{2g\bar{\phi}_q}{m_x^2} \left[ 2\frac{\dot{\rho}_x}{\bar{\rho}_x}\delta\phi_q + \bar{\phi}_q\frac{\delta\dot{\rho}_x}{\bar{\rho}_x} \right] - \frac{\dot{a}}{a} \left[ h\left(\frac{1}{2}\dot{\phi}_q^2 - V(\bar{\phi}_q)\right) - \right. \\ & \left. 6\left(V_q'\delta\phi_q + \frac{2g\bar{\phi}_q\bar{\rho}_x}{m_x^2}(2\delta\phi_q + \bar{\phi}_q\frac{\delta\rho_x}{\bar{\rho}_x})\right) \right] - \frac{\dot{h}}{2}\dot{\phi}_q^2 = \Gamma_q(\delta\rho_x - \frac{\delta\dot{\phi}_q}{\dot{\phi}_q}\bar{\rho}_x) \end{aligned} \quad (1.45)$$

Assuming SDM behaves like a pressure-less fluid the energy-momentum tensor becomes:

$$T_x^{00} = \bar{\rho}_x + \delta\rho_x \quad T_x^{0i} = \bar{\rho}_x\delta u_x^i \quad T_x^{ij} = \mathcal{O}(\delta^2) \approx 0 \quad (1.46)$$

where  $\delta u_x^i$  is the velocity of SDM fluctuations with respect to homogeneous Hubble flow. Interaction terms are explicitly included in the energy-momentum conservation equation:

$$\partial_0\left(\frac{\delta\rho_x}{\bar{\rho}_x}\right) + \partial_i(\delta u_x^i) - \frac{\dot{h}}{2} = -\pi^4 g^2 \left( \frac{3\delta\rho_x}{m_x^3} - \frac{2\bar{\rho}_q'\delta\rho_q'}{m_q^3\bar{\rho}_x} - \frac{\bar{\rho}_q'^2\delta\rho_x}{m_q^3\bar{\rho}_x^2} \right) \quad (1.47)$$

Effect of interactions in (1.47) is negligible and evolution of matter fluctuations is practically the same as the standard  $\Lambda$ CDM case. In the limit  $\dot{\phi}_q \rightarrow 0$ , we find the following relation between spatial fluctuation of  $\delta\phi_q$  and  $\delta u_x^i$ :

$$-V'(\bar{\phi}_q, \bar{\rho}_x) \partial^i (\delta\phi_q) = \Gamma_q \bar{\rho}_x \delta u_x^i \quad (1.48)$$

Equation (1.45) shows that the divergence of quintessence field fluctuations  $\partial^i \delta\phi_q$  follows the velocity dispersion of the dark matter with opposite direction, but amplitude of fluctuations is largely reduced due to the very small decay width  $\Gamma_q$ . With the expansion of the Universe,  $V'(\bar{\phi}_q, \bar{\rho}_x)$  varies only very slightly - just the interaction between SDM and  $\phi_q$  will change when  $\bar{\rho}_x$  decreases by a factor of  $a^{-3}(t)$  - and even gradual increase of the dark matter clumping and therefore the velocity dispersion  $\delta u_x^i$  [17] can not eliminate the effect of decreasing density. The conclusion is that the spatial variation of  $\phi_q$  is very small from the beginning and practically unobservable.

## 1.7 Production and Physics of SDM

Investigation of roles for SDM is not complete without considering mechanisms by which these huge particles can be produced. It is also inevitable that we must be able to find a proper place for them in the zoo of particle physics models.

### 1.7.1 Production

According to our knowledge of the early universe - which is not yet completely proved - SDM like all other particles should be produced in an epoch of preheating/reheating just at the end of inflation. Production of such massive particles however is not an easy task. If preheating/reheating has happened at scales higher than SDM mass, dangerous amount of gravitinos and modulies should be produced which according to most popular models decayed after nucleosynthesis and compromised present observations of primordial deuterium and  $He$ . The energy scale of preheating/reheating therefore should be lower than  $\sim 10^9 GeV$ . Note that there is a difference between the scale of particle production and the maximum temperature during reheating. The boom in particle production is during preheating and it is not thermal i.e. particle production is too fast to permit a thermal equilibrium to happen. Depending on the inflation model after a few (or even in some cases one [115]) oscillation of inflaton at the bottom of its potential, most of its energy is transferred to other particles and interaction between them creates a thermal plasma. Not all species however necessarily arrive to a thermal equilibrium. Species with very weak interaction can decouple before getting thermalized.

During thermalization the production of particles continues both for heavy species and for lighter ones. If the dominant field  $\psi$  - it can be inflaton or another field - is heavier than  $X$ , after its production it is relativistic, otherwise it is not. Here the

field  $X$  can be any field, but we are specially interested on SDM. Production of heavy particles is controlled by what is called  $T_{max}$  which depends on  $\Gamma_\psi$  the decay width of  $\psi$  and on the Hubble Constant at the beginning of reheating. It is the maximum temperature of the plasma before it cools due to expansion. Reheating temperature  $T_{rh}$  depends only on  $\Gamma_\psi$ . It has been shown [116] that today contribution of heavy particle  $X$  which has been produced in a non-equilibrium, non-relativistic condition is:

$$\Omega_X h^2 \approx 1 \times 10^{-5} \frac{g}{2} \left[ \frac{g_*(T_{rh})}{10} \right] \left[ \frac{10}{g_*(T_*)} \right]^2 \left[ \frac{T_{rh}}{100 \text{ MeV}} \right]^5 \left[ \frac{100 \text{ GeV}}{m_X} \right]^4 \quad (1.49)$$

where  $T_*$  is the temperature at maximum particle production,  $g$  and  $g_*$  are internal degrees of freedom respectively for  $X$  and for all species.  $g_*$  depends on the particle physics at preheating/reheating scale. One expects that it is of order 100. It is easy to see that (1.49) leads to  $\Omega_X \sim \mathcal{O}(0.1)$  only if  $T_{rh}$  is close to dangerous limit of  $\sim 10^9 \text{ GeV}$ . For lower reheating temperature  $X$  can not dominate CDM today.

There is however another phenomenon which can produce SDM more efficiently: Strong gravitation at the end of inflation [117]. It has been shown in detail for a hybrid inflation. The difference between quantum vacuum when the massive scalar field begins to roll-down from the false vacuum to its real vacuum at the end of inflation appears as particle production at late time. Constraints from having a successful inflation with enough e-folding, etc. limits the mass of massive fields to  $\lesssim 10^{-3} M_p$ . To order of magnitude precision, the contribution of these heavy particles to the CDM today is (decay of SDM is not included):

$$\Omega_X h^2 \approx \left( \frac{m_X}{10^{11} \text{ GeV}} \right)^2 \left( \frac{T_{rh}}{10^9 \text{ GeV}} \right) \quad (1.50)$$

which for  $m_X \sim 10^{13} \text{ GeV}$  and  $T_{rh} \sim 10^4 \text{ GeV}$ ,  $\Omega_X h^2 \sim 1$ . A more precise evaluation of contribution needs detail knowledge of parameters and a more precise calculation of quantum and classical phenomena. This rough estimation however is enough to show the possibility of having a dominant SDM.

### 1.7.2 Particle Physics

It is usually assumed that highest mass scale in a field theory is less or around the scale of validity of the theory. SDM must have a mass  $\gtrsim 10^{12} \text{ GeV}$ . Therefore if the GUT scale is  $\sim 10^{16} \text{ GeV}$  we expect to find particles of this mass range in GUT candidate theories [14]. The challenge however is to make them meta-stable with a lifetime greater than present age of the Universe. This needs either a very small coupling with high-order non-perturbative interactions or global symmetries similar to baryon number which are very softly and non-perturbatively broken.

Phenomenologically, the decay lagrangian of a field  $X$  can be written as:

$$\mathcal{L} \sim \frac{g}{M_*^p} X \phi^m \psi^n. \quad (1.51)$$

$$p = d_x + m + \frac{3}{2}n - 4. \quad (1.52)$$

where  $\phi$  and  $\psi$  are respectively generic bosonic and fermionic fields.  $g$  is a dimensionless coupling constant and  $M_*$  is Planck mass scale or any other natural mass scale in the theory. This lagrangian leads to a lifetime  $\tau$ :

$$\tau \sim \frac{1}{g^2 M_X} \left( \frac{M_*}{M_X} \right)^{2p}. \quad (1.53)$$

For  $M_X \lesssim M_*$ , the exponent  $p$  must be large and (1.51) becomes non-renormalizable. The other possibility is an extremely suppressed coupling constant. The latter however would not be very natural unless the coupling is effective and related for instance to the physics at a higher scale.

High order lagrangians can be found in (SUSY)GUT models usually inspired by String/M-Theory [118] (heterotic strings and quantum gravity in 11-dim. models). Some compactification scenarios in string theory predict composite particles (e.g. *cryptons*) with large symmetry groups [71] [79] and  $M \gtrsim 10^{14} \text{GeV}$ . The general feature of this class of models is having a very large symmetry group of type  $G = \prod_i SU(N_i) \otimes \prod_j SO(2n_j)$ . Their particle contents includes light particles with fractional charges which have not been observed. It is therefore believed that they are confined at very high energies  $> 10^{10-12} \text{GeV}$ . All of their decay modes are of type (1.51) and their lifetime is in the necessary range.

Models with discrete symmetries seems more natural specially because they have counterparts at low energies. Anomaly cancellation condition restricts discrete groups to  $\mathbf{Z}_2$  and  $\mathbf{Z}_3$  [119]. A number of examples of discrete symmetries exist in Standard Model: Parity conservation and baryon parity which is proposed to be responsible for proton stability [120].

$SO(10)$ -SUSY model is one of the favorite GUT candidates and some implementation of this model may include field with necessary characteristics of SDM. Messenger bosons responsible for communicating the soft SUSY breaking to the visible sector have masses  $\gtrsim 10^{14} \text{GeV}$  [14]. Messengers in representation  $(\mathbf{8}, \mathbf{1})_0$  and  $(\mathbf{1}, \mathbf{3})_0$  of Standard Model  $SU(3) \otimes SU(2) \otimes U(1)$  have been proposed as SDM and  $Y$  - a non-SM particle in which SDM decays [119]. However, in this case SDM would have strong interaction and it would be difficult to explain the large observed bias between dark matter and baryons in present universe. Moreover, in the early universe before nucleosynthesis, its large mass and strong interaction with quark-gluon plasma could create small scale anisotropies with important implications for galaxy formation. These perturbations have not been observed and in fact for explaining the distribution of galaxies today, it is necessary to wash out very small scale anisotropies. By contrast,  $(\mathbf{1}, \mathbf{3})_0$  representation for SDM particles is a more



interesting possibility because in this case they have only weak interaction with ordinary matter and no interaction with photons. This may explain some of features of galaxy distribution and CMB small scale anisotropies.

Other scenarios for SDM decay are suggested: decay through quantum gravity processes like wormhole production [73] and through non-perturbative effects like instanton production [72]. Inspired by recent interest on non-compact extra-dimensions and brane models, decay through gravitation or other fields which propagate in the bulk has been also suggested as the reason for very long life of these particles [121].

## 1.8 Closing Remarks

In this chapter we have tried to find a solution for three puzzles of today physics. In contrast to some other issues like SUSY, macroscopic extra-dimensions, existence of Higgs particles, etc. which are motivated by theories, observational evidence for existence of these phenomena has been accumulated since at least a couple of decades.

The interesting point about models proposed here is that they are all related to one concept: *The existence of a long life superheavy particle*. Physicists love *unifications*, not just for the sake of having an elegant model but also because nature has learned us that there is no isolated entity or law in the Universe. It is in fact a logical necessity. If there is an isolated entity, by definition it does not interact with other entities in the Universe and therefore it is like if it doesn't exist at all.

On the more practical side unification reduces the range of possibilities and simplifies searches. For instance if the model for dark matter and Dark Energy we presented here are the way Nature works, it strongly constrains (SUSY)GUT. Such model must have both a  $X$  type massive particle and intimately connected to it a very light axion type field. Because of this close relation which probably should be due to a conserved global symmetry one can imagine that a sort of seesaw mechanism is responsible for such huge mass separation of  $X$  and  $\phi_q$ . Seesaw mechanism has been also suggested to relate quintessence field to neutrinos [122].

We need yet more and better observations to confirm or rule out this model. As mentioned before observation of UHECRs anisotropy is very preliminary and the data volume as well as our understanding of the distribution of local dark matter in the halo of Milky Way and local group is vague. With ground and space based observatories like Auger, Airwatch, etc. we should better understand UHECRs anisotropy and whether they are more correlated to the halo of the Galaxy or to the nearby extra-galactic sources.

Although the present limit on the amount of the hot DM can not constrain SDM model, a better understanding of its contribution to the total density and its contents can help to understand the physics and the nature of SDM.

Observation of  $w_q$  and its cosmological evolution is crucial for any model of dark energy. Supernova Cosmology Project, High-z SN Project and specially SNAP which will increase the statistics of SN data by few orders of magnitude will give us the opportunity to verify the model, whether  $w_q < -1$  and how far from  $-1$  it is and whether SDM model can explain observations without fine-tuning. Observation of small anisotropy in the DE density and its correlation with matter anisotropy also can be used as a signature of relation/interaction between DM and DE.

The small coupling of  $\phi_q$  with SM particles suppresses the probability of its direct detection. However, the detection of an axion-like particle e.g. the QCD axion can be a positive sign for the possibility of existence of  $\phi_q$ -like particles in the Nature. The interesting point in SDM model is that in contrast to many others, it does not need a very light axion. Moreover, the range of  $\phi_q$  mass which SDM model needs is roughly in the range of axion mass not yet excluded by experiments. There is therefore hopes that next generation of experiments find the QCD or other very light particles.

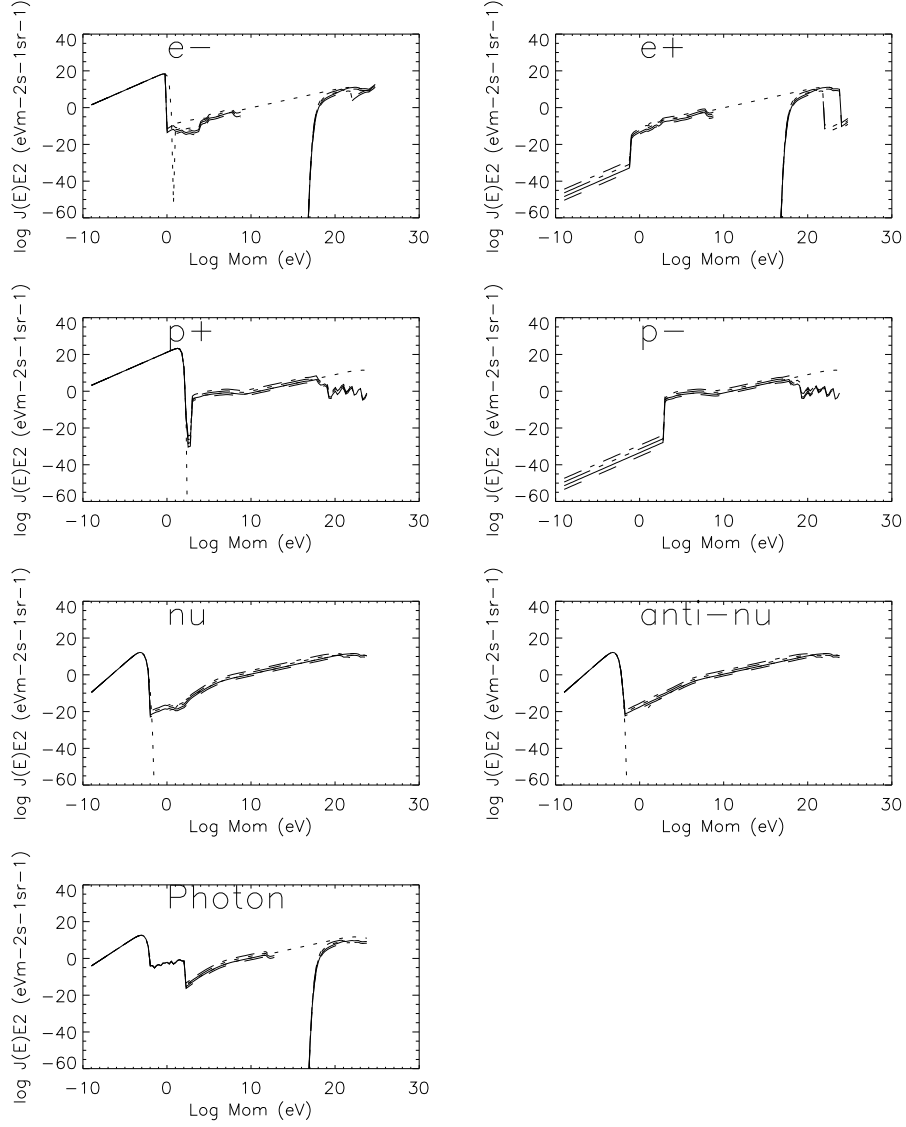


Figure 1.1: Energy flux of stable species. Solid line  $m_{dm} = 10^{24} eV$ ,  $\tau = 5\tau_0$ , dot line is the spectrum without energy dissipation for the same mass and lifetime, dashed line  $m_{dm} = 10^{24} eV$ ,  $\tau = 50\tau_0$ , dash dot  $m_{dm} = 10^{22} eV$ ,  $\tau = 5\tau_0$ , dash dot dot dot  $m_{dm} = 10^{22} eV$ ,  $\tau = 50\tau_0$ .

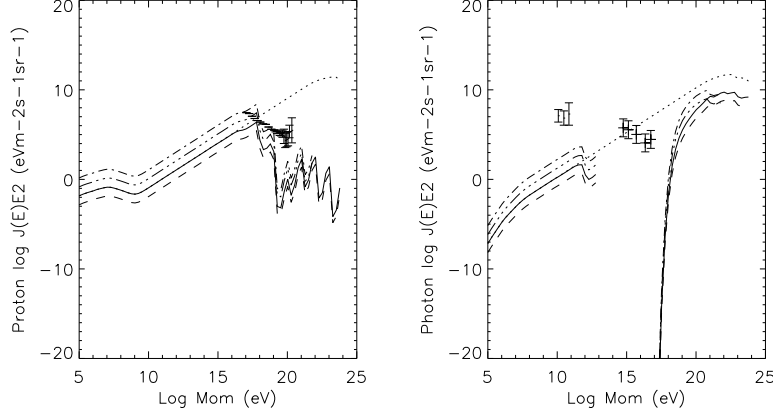


Figure 1.2: Energy flux for protons and photons. Solid line  $m_{dm} = 10^{24}eV$ ,  $\tau = 5\tau_0$ , dot line is the spectrum without energy dissipation for the same mass and lifetime, dashed line  $m_{dm} = 10^{24}eV$ ,  $\tau = 50\tau_0$ , dash dot  $m_{dm} = 10^{22}eV$ ,  $\tau = 5\tau_0$ , dash dot dot  $m_{dm} = 10^{22}eV$ ,  $\tau = 50\tau_0$ . For protons, data from Air Showers detectors [84] is shown. Data for photons are EGRET whole sky background [85] and upper limit from CASA-MIA [86].

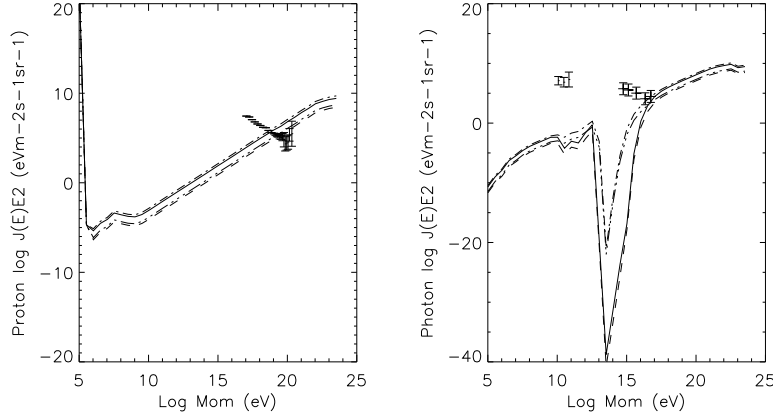


Figure 1.3: Flux of high energy protons and photons in a uniform clump.  $m_{dm} = 10^{24}eV$ ,  $\tau = 5\tau_0$  and  $\tau = 50\tau_0$ . Dash dot and dash dot dot lines presents SDM halo. Solid and dashed lines show a halo of SDM and MACHOs. Data is the same as in Fig.1.2. For protons the effect of increasing lifetime of SDM is more important than presence of MACHOs. Photons trough is more sensitive to presence of MACHOs.

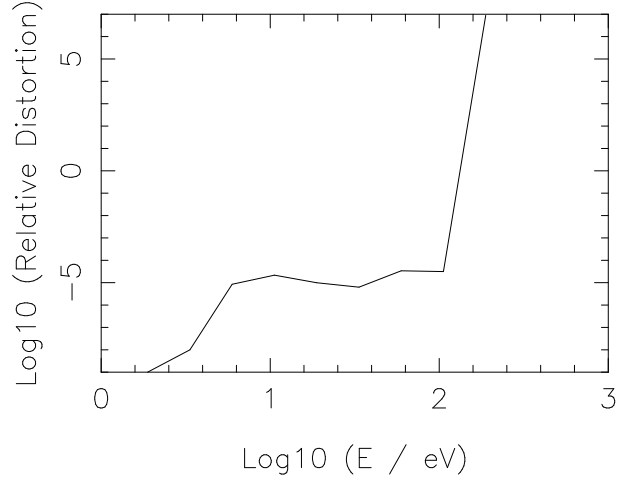


Figure 1.4: Fraction of distortion in photon distribution with respect to a stable DM in energies close to pick of the CMB (Energies are in eV).

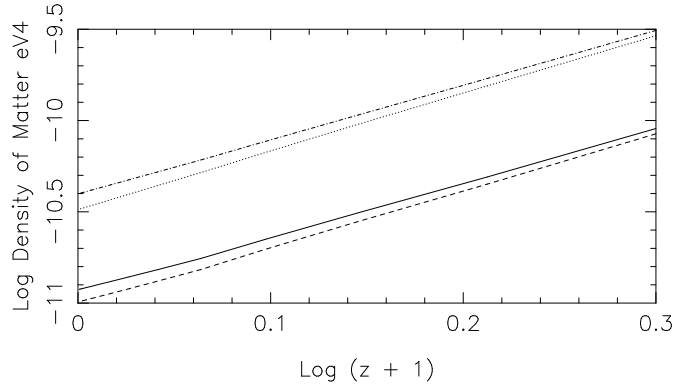


Figure 1.5: Energy density of the Universe. Solid line  $\Omega_\Lambda = 0.7$  and stable DM; dashed line the same cosmology with  $\tau_X = 5\tau$ ; dash dot line  $\Lambda = 0$  and stable DM; dot line  $\Lambda = 0$  and  $\tau_X = 5\tau$ . Dependence on the mass of DM is negligible.

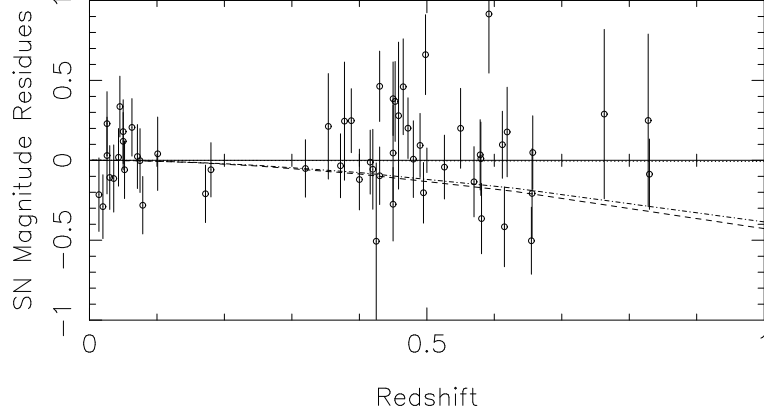


Figure 1.6: Best fit residues with  $\Omega_{\Lambda} = 0.7$ ,  $\tau_X = 5\tau$ . It leads to  $\Omega_{\Lambda}^{eq} = 0.73$ . The curves correspond to residue for stable DM with  $\Omega_{\Lambda}^{eq} = \Omega_{\Lambda} = 0.7$  (dotted);  $\Lambda = 0$  and  $\tau = 5\tau$  (dashed);  $\Lambda = 0$ , stable DM (dash-dot).

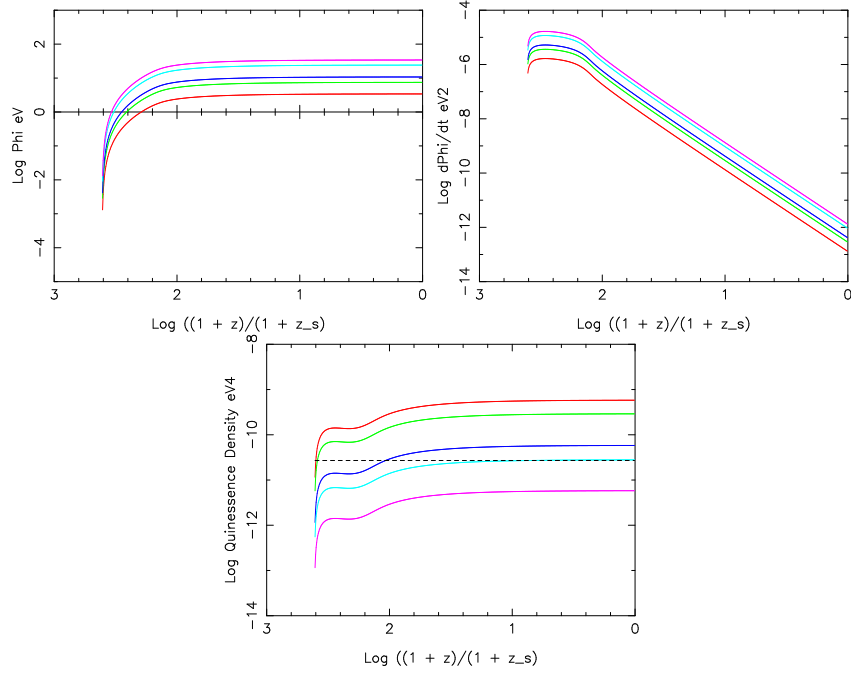


Figure 1.7: Evolution of quintessence field (left), its derivative (center) and its total energy density (right) for  $\Gamma_0 \equiv \Gamma_q/\Gamma = 10^{-16}$  (magenta) (see text for details),  $5\Gamma_0$  (cyan),  $10\Gamma_0$  (blue),  $50\Gamma_0$  (green),  $100\Gamma_0$  (red). Dash line is the observed value of the dark energy.  $m_q = 10^{-6}eV$ ,  $\lambda = 10^{-20}$ .

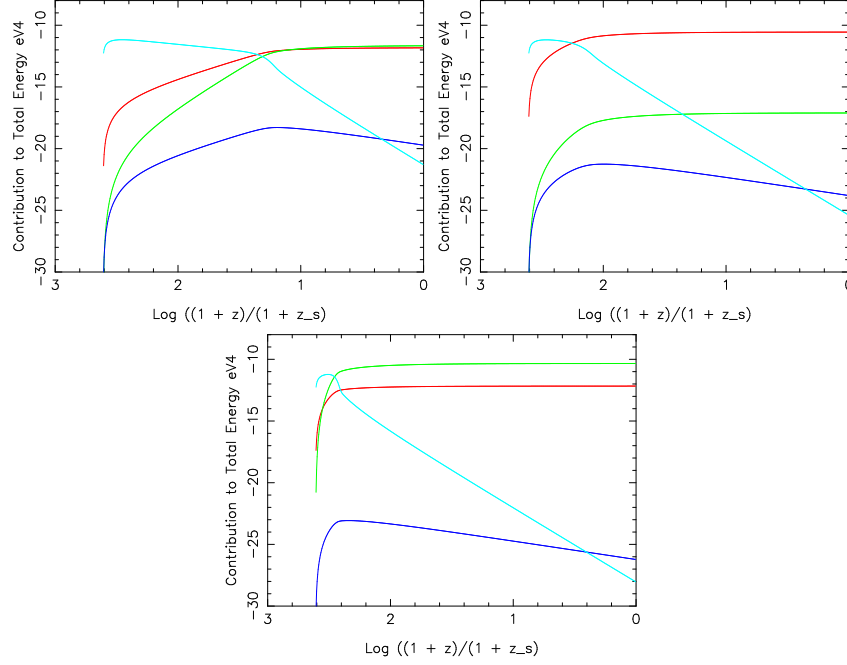


Figure 1.8: Evolution of the contribution to the total energy density of  $\phi_q$  for  $\Gamma_0 \equiv \Gamma_q/\Gamma = 10^{-16}$  and : Left,  $m_q = 10^{-8}eV$  and  $\lambda = 10^{-20}$ ; Center,  $m_q = 10^{-6}eV$  and  $\lambda = 10^{-20}$ ; Right,  $m_q = 10^{-6}eV$  and  $\lambda = 10^{-10}$ . Curves are: mass (red), self-interaction (green), kinetic energy (cyan) and interaction with SDM (blue).

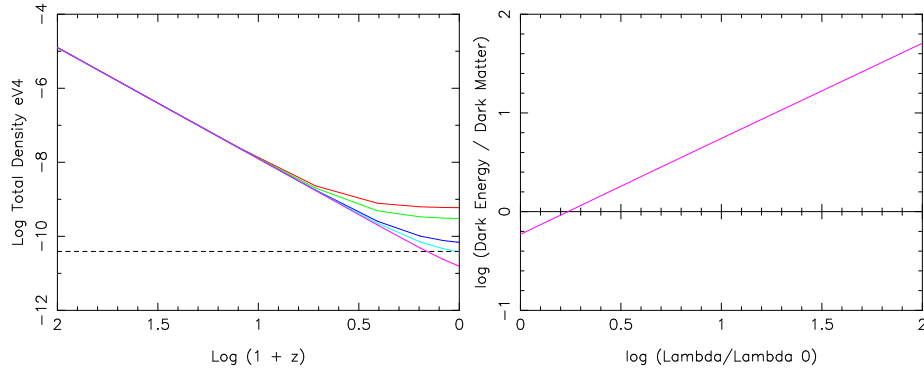


Figure 1.9: Left: Evolution of total density with redshift for  $\Gamma_0 \equiv \Gamma_q/\Gamma = 10^{-16}$  (magenta) (see text for details),  $5\Gamma_0$  (cyan),  $10\Gamma_0$  (blue),  $50\Gamma_0$  (green),  $100\Gamma_0$  (red). Dash line is the observed value of the dark energy.  $m_q = 10^{-6}eV$ ,  $\lambda = 10^{-20}$ . Right: Relative density of dark energy and CDM as a function of  $\Gamma_q/\Gamma$ . The x-axis is normalized to  $\Gamma_0 \equiv \Gamma_q/\Gamma = 10^{-16}$ .

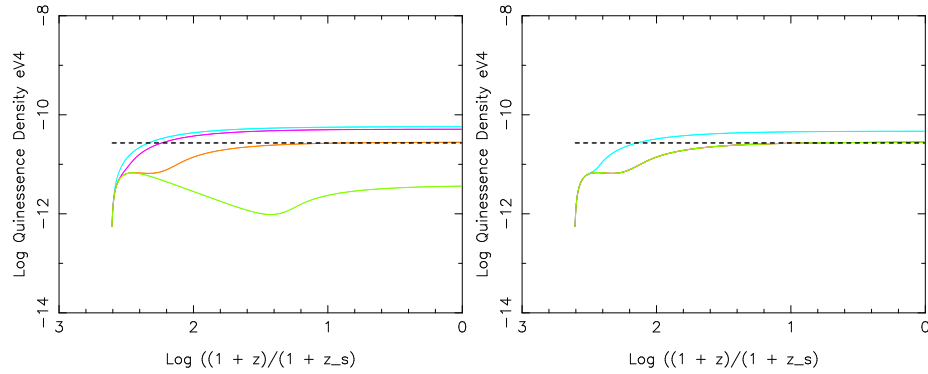


Figure 1.10: Quintessence energy density for: Left,  $m_q = 10^{-3}eV$  (cyan),  $m_q = 10^{-5}eV$  (magenta),  $m_q = 10^{-6}eV$  (red) and  $m_q = 10^{-8}eV$  (green),  $\lambda = 10^{-20}$ ; Right,  $\lambda = 10^{-10}$  (cyan),  $\lambda = 10^{-15}$ ,  $\lambda = 10^{-20}$  and  $\lambda = 10^{-25}$  (green),  $m_q = 10^{-6}eV$ . The difference between quintessence density for the last 3 values of  $\lambda$  is smaller than the resolution of the plot. Dash line is the observed energy density of the dark energy.



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